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INVESTIGATION OF THE EFFECT OF MINIMUM QUANTITY LUBRICATION (MQL) ON THE MACHINING OF TITANIUM AND ITS ALLOYS A REVIEW

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ABSTRACT

In this study, machinability studies of Titanium (Ti) and its alloys construction, under the minimum quantity lubrication (MQL) system has been investigated. Titanium and its alloys, which are made of lightweight metals, are extremely difficult and costly to process. The main purpose of this article is to contribute to the scientific work in this area and assist in the selection of the correct cutting tool, machining operation and cutting parameters during processing of Ti and its alloys. Another aim of the study is to examine the effects of the use of the MQL system in the automotive, aerospace, and space industries on the machinability of Ti and its alloys, which are strategic priorities. In order to reach all these objectives, studies on Ti and their alloys processed with MQL system in the world have been examined and their results have been given.

KEYWORDS: Titanium, Titanium Alloys, Minimum Quantity Lubrication & Review

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A Review Article

INTRODUCTION

The forming of metals with their scientific validity methods, especially machining, is a desirable situation. This is even more important in the lightweight metal groups. Lightweight metals are now more economically more valuable than other metal groups and their value is being enhanced by improved technology. The possibility of machining titanium alloys in the lightweight metal group with minimum material consumption is important in the process of the final product. In addition to the benefits of having low densities of these materials, and optimizing the advantages of industrial applications against their competitors, it also offers a great advantage [1].

In manufacturing, aviation and space industries, especially in the automobile industry, the use of lightweight metals is one of the easiest solutions that can be used to reduce fuel consumption. It is also an important requirement that the materials that can be used can be recycled at the same time [2].

Lightweight metals such as aluminum, magnesium, titanium, beryllium are widely used for fuel saving in manufacturing automotive, aerospace and space industries, which have significant potential use in lightweight material selection [3]. On the one hand, manufacturers are looking to preserve the environmental balance, while on the other hand, the materials they produce need to be economical. Developing lightweight but high-strength materials to make vehicles that consume less fuel is the most important goal of manufacturers, without compromising safety and comfort in the automotive, aerospace and space industries. [4].

Industrial alloys such as aviation, aerospace and automotive are remarkable materials [5]. This is usually

due to the low thermal conductivity, high chemical reactivity and high hardness properties of titanium. All of these properties are possible by applying as the best lubricant approach to increase tool life, reduce cutting temperature and increase surface roughness [6].

Titanium and its alloys have high strength-weight ratios, good fatigue properties and excellent corrosion resistance [7]. Commercially pure titanium and titanium alloys are not magnetic. Because of this feature, it is frequently used in submarines, aircraft, medical devices and at sea, on boats, oil and gas platforms. The thermal conductivity of all titanium alloys is quite low for a metal. Temperature significantly affects the physical properties of titanium. Aluminum grades, predominantly high strength materials, can retain tensile and tensile strengths to relatively high temperatures as compared to commercially pure materials. Contrary to the tensile strengths of titanium alloys, there are excellent high cycle fatigue strengths. Toughness depends on the interlocking texture, microstructure, strength and composition [7].

Since titanium is a poorly conductive material, the heat generated during the cutting process cannot be dissipated rapidly [8]. For this reason, a large majority of the heat is concentrated on the cutting edge and on the cutting surface. The use of minimum quantity lubrication (MQL) facilitates the machinability of the material, in order to remove these adverse effects. Due to this reason, research on the use of the MQL method during the processing of titanium and its alloys has shown a significant increase over the last decade years [9].

The Figure 1. shows the number of studies on the use of MQL during the processing of titanium and its alloys in the last decade [9]. Due to the advantages of using MQL, the investigation of the effect of the use of MQL on lightweight metals has become scientifically important.

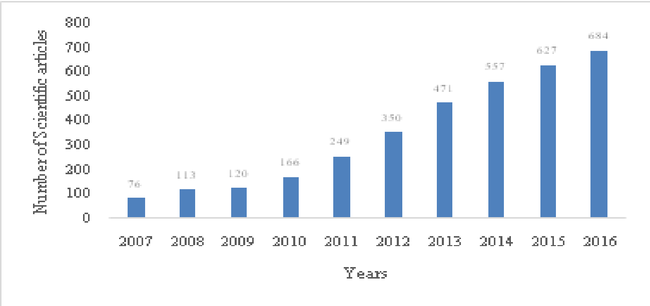

Figure 1: The Number of Scientific Articles in "Google Scholar" [9]

Cooling fluids play an important role in reducing thermal or mechanical problems during cutting [10]. With the lubrication process, friction is reduced and the resulting chips are removed from the cutting zone, helping to extend the tool life and increase the machining quality [11]. However, the use of cooling fluids has an important place in both production costs and threatens the environment and human health [12,13]. For this reason, it is an important research topic for today's researchers to reduce the amount of cooling fluid used during cutting due to the employee health and environmental influences as well as the desire to reduce production costs.

This study examines recent studies on the use of different cooling-lubrication methods during the processing of Titanium and its alloys commonly used in the industry. This will then aid the researchers in studying the field and is intended not to lead to the applicability of cooling-lubrication methods, but also to the applicability of cutting parameters. For this reason, it has been emphasized the application of the minimum amount of lubrication system with the conventional methods in Titanium and its alloys.

MINIMUM QUANTITY LUBRICATION TECHNIQUE (MQL)

The MQL is the system used to cool the surface of the cutting tool and workpiece, usually with oil and air mixture, with very small oil droplets mixing with air [14]. An alternative to MQL applications, for flood or dry cutting fluid application is presented as an environmentally friendly and economically useful method [15]. This cooling technique is sometimes called dry lubrication or micro lubrication. The main benefits of MQL are to reduce the consumption of cutting fluid, to save costs, to reduce environmental impact, to improve overall performance in cutting, and to surface quality [16]. MQL machining has been regarded as one of the practical ways for clean manufacturing in the context of sustainable production [17]. Aerosol acting as the lubricant.

This MQL system includes an atomizer, a cutting fluid carrier, a discharge nozzle. The atomizer operates as an injector in which high-pressure air is used to atomize the coolant. The atomized cooling is sent to the air handling zone in a low-pressure distribution system [18]. Due to the venturi effect in the mixing chamber, the partial vacuum-absorbs the cutting fluid in the oil reservoir and is held here at a constant hydraulic load. The air passing through the mixing chamber atomizes the stream of cooling fluid into the aerosol of micron-sized particles. If this aerosol cutter is sprayed in mist, it works as lubricant as the cooling medium and penetrates the depths of the tool-workpiece interface.

The cutting fluid can be divided into two categories according to the shape of the cutting area: MQL technique, external distribution and internal distribution. The main difference between these two can be explained by Figure 2. In an external feed system, the aerosol prepared in the atomizer is sent to the cutting zone by means of a nozzle which is externally mounted on the machine tool as shown in Figure 2(a) [19]. In the internal delivery system, the cutting fluid and air are mixed in the nozzle and the mixture is sprayed into the cutting zone by means of a channel as shown in Figure 2(b) [20].

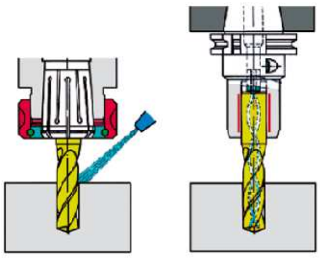

Figure2. (a) External and (b) Internal Delivery System [19]

In peripheral milling, or when the tool is parallel to the work piece, the dead zone starts closer to 100 degrees from the nozzle. The nozzle should be placed close to horizontal spraying the tool before it enters the cut to fluid delivery. It is placed before entering the cut, not on the back side, so no chips or turbulence interrupts the aerosol flow. Figure3 shows the optimum position of the external nozzle for peripheral milling [21].

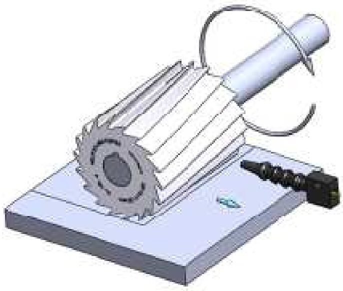

Figure 3: Optimum Position of External Nozzle for Peripheral Milling [21]

The MQL systems for external feeds are suitable for the reprocessing of machine tools since the required spray nozzles can be easily mounted on the spindle head. This system is particularly suitable for simple standard operations, sawing, drilling, milling and turning [19]. This type of lubricant designation is limited by the tool's accessibility to the cutting edge as well as by different tool lengths and diameters. Table 1 lists the main advantages and disadvantages of external lubricant [19].

Using MQL systems with internal feeds provides direct contact to the contact point through the precision aerosol tool. The lubricant is continuously present at critical points throughout the entire processing sequence. This is advantageous for drilling very deep holes and for working at very high cutting speeds. Converting to this system can be costly because the medium has to feed through the machine shaft. Some systems can be controlled directly with the machine tool control system; the lubrication system settings for the required amount of oil and compressed air can be adjusted automatically when a set is changed. For these lubrication systems in automatic production, it is not necessary to manually adjust the system parameters. Table 2 gives an overview of the advantages and disadvantages of the internal feed [19].

Attanasio et al. [20] named these two techniques as external supply and internal supply MQL system, as shown in Figures 4 (a) and (b). Internal supply The MQL system has some advantages over the external supply system. The aerosol that acts as a cutting fluid lubricant when the steam present in the cutting zone performs the action of high pressure, compressed air cooling.

Table 1: Use of MQL with External Feed [19]

<table>
<tr><th colspan="2">External Feed</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Simple Adaptation</td><td rowspan="2">Limited Adjustment Options for the Nozzles due to Different Tool Lengths and Diameters</td></tr>
<tr><td>Low Investment Cost</td></tr>
<tr><td>Little Work Required to Retrofit Conventional Machine Tools</td><td rowspan="3">Possible Shadowing Effects of the Spray jet When Machining</td></tr>
<tr><td>Rapid Response Characteristics</td></tr>
<tr><td>No Special Tools Required</td></tr>
</table>

Table 2: Use of MQL with Internal feed [19]

External Feed	
Advantages	**Disadvantages**
Optimal lubrication at the cutting point (for each tool, even for inaccessible point)	Special tools required
No scattering or spray loses	High investment costs
Optimized lubrication quantity for each tool	Suitability of the machine is required

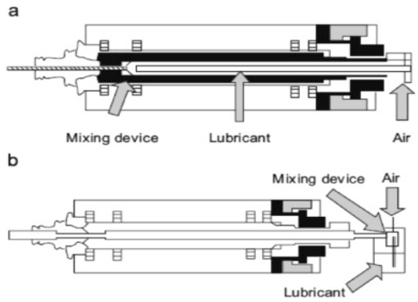

Figure 4: Different Types of MQL Feed Systems (a) Internal, (b) External [20]

EFFECTIVITY OF MACHINING WITH MQL

Various researches have been carried out for years in the production of cutting fluids used in the manufacturing process, a positive effect on tool life and surface roughness, and a protective approach to the environment and human health. Therefore, reducing the amount of cutting fluid used and minimizing adverse effects on human health can provide the needs we need. The MQL systems developed in this direction are intended to meet the requirements for machining the part using cutting fluid. The effect of the MQL method plays an important role in determining the effectiveness of different machining methods performance of workpieces [18]. For this reason, dividing the titanium workpieces into categories related to different processing methods may provide a better comparison of the efficiency of the MQL with the process. For this reason, it is possible to better compare the efficiency of the MQL with respect to machining methods by separately examining the studies of the titanium workpiece in different these methods.

Turning of Titanium and Its Alloys

In this work by Ramana [22], the effects and optimization of surface parameters were investigated during the turning of Ti-6Al-4V alloy under dry, flooding and minimum quantity lubrication (MQL) conditions using Taguchi's robust design methodology. The results show that dry, flooding and MQL conditions are comparable and show better performance and improvement in reducing the surface roughness of MQL compared to dry and flooding lubricant conditions. The CVD coated tool performs better when compared to uncoated and PVD coated tools. It has also been observed from ANOVA that the feed rate has a great influence on the surface roughness.

In this study by Gupta and colleagues [23], the effect of cutting fluid types, three processing parameters (cutting speed, feed rate and approach angle) were chosen when working the titanium alloy in the nano-liquid in minimum quantity lubrication environment and these parameters were used to calculate the cutting force, tool wear and surface roughness were investigated. The experiments were carried out based on the response surface methodology and a combined objective function was generated using the output parameters. The results were analyzed and compared with the traditional desired function approach technique.

In a study by Nipanikar [24], the effect of surface roughness and the effect of flake shear on the cutting parameters during processing of titanium alloy Ti-6Al-4V ELI (Extra Low Interstitial) using a PVD TiAlN cutting tool in the minimum quantity of lubricating medium was investigated. For the experiment design, full factorial Taguchi method is used. Titanium alloy turning was applied and the machining parameters were found to be fixed at cutting speed (50, 65, 80 m/min), feed rate (0.08, 0.15, 0.2 mm/rev) and cutting depth 0.5 mm. The obtained results show that, contribution of 44.61% at feed rate and additive at cutting rate contribute 43.57% to surface roughness, 53.16% to cutting tool and 26.47% to tool flank wear at cutting speed.

In this work by Deiab and colleagues [25], we investigate the effect of six different strategies on tool wear, surface roughness and energy consumption during turning of Ti-6Al-4V alloy, using uncoated carbide tool at specific speed and feed rate. It has been determined that, the use of rape seed vegetable oil is a generally viable alternative in MQL and MQCL configurations. It has been verified that, the use of vegetable oil as lubricant for processing is advantageous.

In this work by Oliviera and colleagues [26], investigate the effect of the feed rate, depth of cut, cooling system, and type of tool on the responses of the titanium alloy on the surface roughness, passive force, feed rate force. This study examines the effect of feeding speed, cutting depth, cooling system and tool on the reaction of the specimens during the turning of the titanium alloy: surface roughness, passive force, feed rate force, shear force and micro hardness. Experimental tests were carried out with 4 mm diameter workpieces and surface roughness, micro hardness and cutting efforts were analyzed. The results showed that the lowest surface roughness was obtained using the TPMT coded carbide tool and lower input parameters, but the most important parameter was the feed rate. Cutting efforts were influenced by feed rate and cutting depth. On the other hand, the cooling system does not show good efficiency in cutting efforts. However, the geometry of the tool and the Minimum Quantity Lubrication system are more effective to cause hardening on the micro-scale of the material surface.

Milling of Titanium and Its Alloys

In the work of Kaynak et al. [27], a new generation of Ti-5553 alloys with a potential to replace Ti-6Al-4V, which is widely used due to its superior properties such as high corrosion and fatigue resistance, it is presented. The experimental part of this work involves the orthogonal cutting process of the Ti-5553 alloy under conditions of dry, cryogenic, minimum quantity lubrication (MQL) and high pressure cooling fluid. Various cutting speeds have been considered to observe the chip-tool contact length, forces, temperature, chip morphology caused by various processing conditions.

In this work by Park et al. [28], the machinability of the Ti-6Al-4V alloy by using the MQL and cryogenic system and, the dry and wet processing method are compared. Liquid nitrogen has been used for cryogenic processing, with specially designed cryogenic spray systems. In addition to conventional MQL, a new MQL technique, mixed with a small amount of lubricant (~ 0.1%) of exfoliated graphite nano-platelets, was tested to compare with other techniques. The results obtained showed that, both cryogenic and MQL processing performed better, when compared to dry and wet processing. However, for cryogenic processing, exposure to LN2 causes the thermal gradient on the cutting tools and the hardening of the titanium alloy during processing, resulting in excessive tool wear and micro-fracture and increasing shear forces.

In this study, which is designed to investigate the machining performance of milling Ti-6Al-4V made by Park and colleagues [29] using various cooling methods, cryogenic minimum quantity lubrication (MQL) and flood cooling methods

have been investigated. Particularly, the effect of the inner and outer spraying methods on the cryogenic working has been analyzed by a specially designed liquid nitrogen spraying system, evaluating tool wear and cutting force in cutting conditions. Shear force was also analyzed for tool breakage detection. As a result, it has been observed that the combination of MQL and internal cryogenic cooling improves tool life by up to 32% compared to conventional cooling methods. Thanks to this combination of side-end milling cooling and lubrication strategy, the sheer force is also significantly reduced.

In this study by Kim et al. [30] both nano-fluid minimum quantity lubrication (MQL) and the titanium alloy using a cold gas (Ti-6Al-4V) micro end milling operation the milling force, coefficient of friction, the influence of the surface roughness and tool wear was investigated. These analyzes were made according to the types of nano-fluids and weight concentrations. In general, experimental results show that, cold CO2 gas cooled nano-fluid MQL is effective in reducing milling forces, friction coefficients, tool wear and surface roughness. At the lower concentration (0.1 wt.%) the nano-diamond nano-fluid has been shown to be more effective in reducing force, friction coefficient and tool wear. On the other hand, high concentration (1.0 wt.%) has been found to be more advantageous, to reduce surface roughness.

In this work by Okada and colleagues [31], the use of a minimum quantity of lubrication (MQL) method at the end mill, was investigated using a coated carbide tool for stainless steel and titanium alloy workpieces. The effects of MQL were mainly evaluated by tool side temperature, cutting force, tool wear behavior and surface roughness. When the stainless steel and titanium alloy were milling using MQL at a cutting speed of v=25 m/min, the tool side temperature decreased by about 50 and 100 °C, respectively. Especially, at low cutting speeds, the effect of MQL on the tool side surface temperature is clearly observed. On the contrary, it was observed that the tool side temperature in the MQL section of the titanium alloy is higher than that of the dry section when v=100 m/min or more.

CONCLUSIONS

The effectiveness of MQL for machining has been presented in this review drawing on the substantial available literature. In terms of machining effectiveness, MQL has shown to have great promise with traditional machining operations, namely turning, milling and drilling. Improvements resulting from the use of MQL were reported for various aspects of machining, such as tool wear, surface roughness, cutting temperature and cutting force

Recent developments in MQL include the introduction of nanoparticles MQL cutting fluids, as well as hybrid MQLs by combining cooled air/gas, such as cooled air and supercritical CO_2 with MQL. These developments have shown to be successful, in terms of increasing the lubricity and cooling effect of a MQL system.

The main results of this study, in which, the application of the MQL system to the processing of titanium and its alloys by the machining process is summarized.

- Cutting temperatures resulting from the processing of titanium and its alloys negatively affect tool life, cutting force and surface roughness. Since the MQL system directly affects the cutting zone, it minimizes the negative effects.
- MQL system gives better results than the dry process in terms of tool life and cutting force.
- The MQL system provides less power consumption than either the wet or dry process when the power consumed during processing is taken into consideration.

While the MQL system gives close results with wet processing in terms of workability criteria, it is a good alternative to cooling and lubrication when considering the cost of processing, environmental pollution and worker health. Although the MQL system in the lightweight materials is costlier than a special system and extra coolant-lubricant materials, it is more preferable than the dry process because it provides better results in terms of tool wear, cutting force, heat generated in the cutting zone, tool life and surface roughness.

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